FACT SHEET

Links Between Coffee Leaf Rust, Weather, and Climate: A Literature Review

IRAP
An IRI and UA Partnership

INTRODUCTION

Coffee leaf rust (CLR) is the most destructive coffee disease in the world (Luaces et al., 2011) and has negatively impacted coffee production since the late 1800s (McCook, 2006). CLR damages coffee plants and decreases yields, which in turn reduces labor, influences wages, affects market prices, and inhibits farmers' ability to manage their farms. The cumulative effects reduce farmer income, affecting livelihoods and food security, and force some to abandon their farms or switch to different crops altogether (WCR, 2014).

In recent years, CLR epidemics have been particularly damaging in Latin American and the Caribbean (Avelino et al., 2015). In 2012–2013, CLR epidemics cost farmers in these regions an estimated $500 million in lost production alone (ICO, 2013) and led to reduced production for at least two years (Avelino et al., 2015). Efforts to minimize the impacts of future outbreaks have led to research on new coffee varieties and, in the case of Colombia, large-scale programs to replace susceptible varieties with more resistant ones (De Silva and Tisdell, 1988; Arneson, 2000; Avelino et al., 2015). Capacity-building efforts that enable better management also have been implemented (e.g. De Silva and Tisdell, 1988; Staver et al., 2001; Shiomi et al., 2002; Santamaria and Bayman, 2005; Jackson et al., 2012; Zambolim et al., 2016). These effots will be aided by the development of early warning systems (e.g. Alves et al., 2011; Luaces et al., 2011; Perez-Ariza et al., 2012; Avelino et al., 2015) and decision-support tools (e.g. Meira et al., 2009; Cintra et al., 2011). The provision of climate-related information has been offered as a vital element in these efforts (Avelino et al., 2015).

The causes of and responses to CLR are complex and demonstrate the multi-faceted relationship between disease characteristics, environmental conditions, climate and weather triggers, and the human actions that promote or hinder the disease. Although there are many factors to consider when managing CLR, climate and weather information has the potential to help farmers with disease management, but has thus far been under used. This document is step toward assessing the state of knowledge roles of weather and climate in supporting the growth and spread of CLR It draws from more than 50 peer-reviewed articles, reports, and presentations related to CLR and coffee management to provide a summary of the current state of knowledge on the climate and weather influences on CLR.

CLR Life Cycle

CLR is caused by the fungus Hemileia vastatrix, which is an obligate parasite; it requires a host—coffee—to survive and reproduce. The fungus begins its life cycle as a microscopic spore. Spores deposited on the underside of a coffee leaf during favorable weather conditions will germinate and infect the leaf, penetrating it through the stomata and growing, or colonizing the leaf, to extract nutrients (Nutman and Roberts, 1970; Arneson, 2000; Kolmer et al., 2009). Once the spores begin germinating, the infection process usually is completed within 24 to 48 hours, provided there is a continuous presence of moisture and the temperature ranges between 15 and 30 degrees Celsius. After infection, the fungus will grow and produce new spores in about three to four weeks (Moraes et al., 1976 cited in Zambolim et al., 2016). The time needed for germination, infection, and the production of new spores, and the extent of the infection are largely determined by weather conditions, particularly temperature and moisture (e.g., Rayner, 1961; Avelino et al., 2004); the damage caused to the leaf during the infection process is also dependent on plant health (Rayner, 1961; Bock, 1962; Nutman and Roberts, 1963). Water plays a key role in the fungus's survival and reproduction, but in the absence of water, dry spores can survive on leaves for about six weeks (Arneson, 2000).

The first signs of infection are pale yellow spots on the under side of the coffee leaves, which gradually increase in diameter, forming lesions that are orange and powdery (Arneson, 2000; Figure 1). The lesions tend to be concentrated toward the margins of the leaves where dew and rain-drops collect (Arneson, 2000). Over time, the area surrounding the lesions typically becomes discolored as the fungus inhibits production of chlorophyll; however, sometimes the contrary is seen—particularly in older leaves—where a green halo forms around the lesions. This in turn impedes photosynthesis in the infected leaf, depriving it of nutrients and causing it to drop from the plant prematurely. The loss of leaves can hinder branch growth and decrease crop yield, most acutely during the season following infection (Avelino, 2013).

Climate, Weather, and Coffee Leaf Rust

The primary weather-related variables that affect CLR include temperature, moisture, and wind. These variables influence CLR at difference stages in its life cycle: temperature affects germination, infection, and the time required for the fungus to produce new spores; moisture (in the form of soil moisture, leaf wetness, or rainfall) affects germination, infection, and spore dispersal; and wind primarily affects dispersal, though it can influence temperature and moisture as well (Figure 1).

The CLR life cycle is also influenced by factors other than climate and weather that are important at different stages. For example, stomatal density affects the fungus's ability to penetrate the leaf; if the density of stomata on the underside of leaves is high, then there are more areas where the fungus can penetrate into the leaf and form lesions that produce spores (Silva et al., 1998; Avelino et al., 2004). Other factors such as fruit load also play a role in the disease. Each of these factors are influenced by management practices, creating a dynamic and complex environment in which CLR proliferates. Additional non-climate and weather variables are discussed further down; however, the focus of this factsheet is on the climate and weather influences on CLR. By influencing these climate and weather variables, shade, though not directly weather-related, has both positive and negative effects on CLR and is therefore discussed throughout.

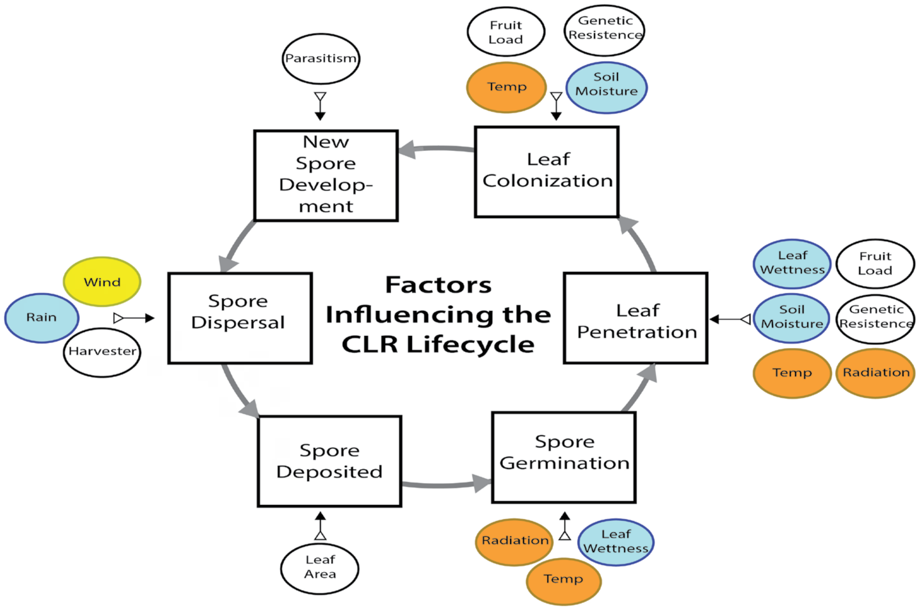

FIGURE 1. I INFLUENCES OF CLIMATE AND WEATHER VARIABLES ON DIFFERENT CLR LIFE CYCLE STAGES; FIGURE MODIFIED FROM AVELINO ET AL., 2014. COLORS DENOTE CLIMATE-RELATED INFLUENCED.

Temperature

Germination and infection

Temperature plays a significant role in several lifecycle states (Figure 1), in addition to affecting pathogen survival and the plant's ability to respond to the infection (Sutton et al., 1984; Alves et al., 2011). Temperature most strongly influences germination and infection (i.e. penetration and colonization) (Nutman and Roberts, 1963). Specifically, during germination, CLR is most affected by daily minimum and maximum temperatures, diurnal temperature variation (the difference between the high and low temperatures that occur during the same day) and the frequency of cold nights and warm days.

Optimal temperatures for spore germination and infection are between about 21 and 25 degrees C (Waller, 1982; Kushalappa et al., 1983; De Jong et al., 1987), although some researchers have specified a narrower optimum of about 22 to 24 degrees C for Arabica and Conilon coffee (De Jong et al., 1987; Capucho et al., 2013). Temperatures below 18 degrees C and above 28 degrees C delay the production of new spores (Zambolim et al., 2005 cited in Zambolim et al., 2016), while temperatures below 15 degrees C and above 30 degrees C more severely suppress germination and infection (Rayner, 1961; Nutman and Roberts, 1963; Kushalappa et al., 1983; De Jong et al., 1987). As average minimum temperatures (typically experienced at night) increase, the incidence and severity of CLR epidemics also increases. Conversely, the more frequently temperatures fall below the minimum threshold of 15 degrees C, the lower the infection rate and severity of CLR (Brown, 1995).

Geographical influences on temperature

Temperature is largely influenced by geography: higher elevations are cooler than lower elevations, and shaded areas are cooler than non-shaded areas. As a result, the incidence of CLR historically has varied by elevation; temperatures at higher elevations are below optimal for CLR and temperature fluctuation is greater throughout the day (Bock, 1962; Brown et al., 1995; Avelino et al., 2006; Lopez-Bravo et al., 2012). However, increased global temperatures have made higher elevations more hospitable to CLR in recent years (Avelino et al., 2015). With the expectation that temperatures will continue to rise in the future, more areas at higher elevations likely will become favorable to CLR (Alves, 2011).

Influences of shade on Temperature

In general, where CLR is present, shaded areas tend to create environments closer to the optimum temperature for CLR, while temperatures in unshaded areas are more likely to be less ideal for rust spore germination and infection (Lopez-Bravo et al., 2012). Unshaded coffee also receives more direct solar radiation, which can also be damaging to the disease (Avelino et al., 2004).

Water

Germination and Infection

Moisture plays a key role in the progress of CLR, affecting the germination, infection, and spread of spores and the overall health of the coffee plants (Avelino et al., 2006). Although high humidity (greater than 80 percent) for 24 hours or longer increases spore germination and rust infection (Capucho et al., 2013), humidity by itself in the absence of free water is not enough (Kushalappa et al., 1983; Avelino et al., 2006). Free water on the leaves for at least six hours is necessary for spore germination and infection, although germination alone can occur in as little as three hours if spores are fresh and conditions are optimal (Rayner, 1961), and continuous leaf wetness for 20 hours is optimal for high infection rates greater than 80 percent (Kushalappa et al., 1983). Additionally, the longer leaves remain wet, the greater the severity of the disease and thus damage to the plant (Kushalappa and Chaves, 1980 cited in Zambolim et al., 2016). Any interruption of spore germination by drying—even if the leaves are re-wetted—will prevent infection (Nutman and Roberts, 1963).

The timing of rainfall is also important to rust development (Kushalappa and Eskes, 1989). There is some evidence that an early onset of the rainy season can lead to a longer period during which CLR can thrive, resulting in greater damage to coffee crops and plants later in the year (Rayner, 1961; Georgiou et al., 2014).

Effects on plant recovery

Based on observations that irrigated coffee trees tend to have more rust than trees under water stress (Hoogstraten et al., 1983), high soil moisture is thought to increase the rate of infection and the rate at which new spores are produced. Although this may seem counterintuitive, as high soil moisture might indicate low water-stress for the plant, saturated soils may actually inhibit the plant's ability take in nutrients, thus slowing growth and recovery from CLR infection (Cristancho et al., 2012). The increased rate of infection in conditions of high soil moisture and humidity may also be due to the increased opening of leaf stomata, which makes the leaves more susceptible to penetration by the CLR fungus.

Dispersal

Water also plays a critical role in the local dispersal of CLR spores. When it rains, rust spores are dislodged from leaves and carried in water droplets to other leaves on the same plant or sometimes to other plants. This mechanism is known as "rain splash" and is responsible for CLR spore dispersal over short distances (Burdekin, 1960; Nutman et al., 1960; Bock 1962; Boudrot et al., 2016). More rain, however, does not always mean more rust. Heavy, continuous rains may actually not be conducive to outbreaks of CLR because in these conditions spores can be washed off leaves entirely, reducing spread to other plants and severity of the disease (Avelino, 2013).

Influences of shade on moisture and dispersal via rain splash

Shade can help maintain a humid environment for plants, which keeps leaves wet for longer and can increase CLR infection (Rayner, 1961; Nutman and Roberts, 1963; Avelino, 2006). Shade may also increase spore dispersal via rain splash, because water collected on shade trees may cause larger rain drops moving at faster speeds to hit coffee plants, thus dislodging more spores than if shade trees were not present (Boudrot et al., 2016).

Wind

Dispersal

Wind plays an important role in spore dispersal (e.g. Rayner, 1961; Burdekin, 1960; Martinez et al., 1975) and may also affect leaf wetness and overall plant health. Wind needs to be sufficiently strong (greater than about 7mph) to dislodge spores from leaves and transport them to other plants (Rayner, 1961) and higher speed winds tend to transport larger quantities of spores than slower winds (Martinez et al., 1977). But, once this occurs, wind can carry spores up to 1000 meters into the air and over distances of hundreds to perhaps thousands of kilometers. However, infection is more likely when clusters of spores germinate together (rather than as individual spores), so over long distances spores may become too dispersed to effectively spread the disease (Bock, 1962).

When humidity is high or when it is raining, spores cannot be easily carried in the air (Becker, 1977 cited in Waller, 1982; Martinez et al., 1977). Rain is the primary mechanism by which spores are removed from the air and returned to the land (Martinez et al., 1975).

Wind can also affect plant health. Storms and hurricanes often severely damage coffee trees and reduce coffee yields (Eakin et al., 2011). Plants that are stressed by storm damage may be more susceptible to CLR and other disease. Shade trees, however, can decrease wind speed and help prevent damage to coffee trees, which help them be more resistant to diseases and pests (Lopez-Bravo et al., 2012).

Shade influence on wind

Under calm conditions or in wind-protected areas—particularly in the shade—temperatures are more likely to remain in the optimal range and leaves may stay wet longer, thereby leading to CLR-favorable conditions (Avelino et al., 2004). Reduced wind may also allow more water to accumulate on leaves, which may enhance dispersal by rain splash (Boudrot et al., 2016). However, reduced wind speed under shade also reduces wind dispersal of rust spores (Boudrot et al., 2016).

Other Factors Influencing CLR

In addition to climate and weather, a number of other factors related to agricultural practices and other environmental stressors influence incidence and severity of CLR in any given place or time. These include coffee plant exposure to shade or sun, the density of coffee plants, the amount of viable CLR spores remaining from the previous year, soil quality, and human dispersal of spores. Additionally, some varieties of coffee—particularly Arabica—are more susceptible to infection than others.

Agricultural practices: Shade, plant density, and human dispersal mechanisms

Shade has counteracting influences on CLR that make it challenging to assess the net effect. Shade affects temperature, moisture, and wind, as well as crop yield, plant characteristics, and biological controls of CLR (Table 1). The combined effects of shade on CLR illustrate the numerous interactions and countering effects that alter environmental conditions and present challenges for CLR management efforts (Boudrot et al., 2016).

Influences Of Shade on Weather Factors	Increase or Decrease	Rationale
Temperature	+	Shade can moderate temperature by blocking direct sunlight and wind, leading to higher and low minimum and maximum temperatures than non-shaded areas.
Leaf Wetness	+	Shade tends to maintain humid environments, allowing leaves and soil to stay wet longer.
Soil Moisture	+	
Rain Splash	+	Shaded areas tend to cause raindrops to be larger and fall harder on plants during heavy downpours than non-shaded areas, causing spores to be more easily dislodged from leaves. In light rains, shade may intercept the raindrops entirely preventing rain splash.
Dew	–	Shade tends to reduce the amount of dew that gathers on leaves, which can support CLR development.
Wind Dispersal of Spores	–	In light rains, shade may intercept the raindrops entirely preventing rain splash.
Stomatal Density	–	Under shade, the number of stomata per unit of area (the density) tends to be less than on plants in full sun.
Lecanicillium Lecanii	–	Shade provides more optimal conditions for the fungus Lecanicillium lecanii, which is a predator to CLR.
Fruit Load	–	Shade-grown coffee tends to produce less fruit than plants grown in full sun. This can help plants be more resistant to CLR; however, following years with high-yields, plants grown in full sun tend to experience lower production.
Radiation	+ –	Solar radiation is harmful to CLR. Plants in the shade receive less direct radiation, which allows CLR to develop more easily. Leaves in full sun are more susceptible to CLR than those in the shade.
Leaf Area Index	+	Under shade, leaves tend to be larger than on plants in full sun, which provides a larger surface area onto which CLR spores can land and develop.

TABLE 1. THE INFLUENCE OF SHADE ON WEATHER AND NON-WEATHER FACTORS (+ INDICATES AN INCREASE IN RUST; - INDICATES A DECREASE IN RUST)

As discussed previously, shade can create optimal temperature and moisture conditions for CLR, with the exception of dew, which tends to be less prevalent in shade (Avelino et al., 2004), but has differing effects on spore dispersal depending on moisture conditions. Moisture decreases spore dispersal by when conditions are dry and increases dispersal by rain splash during wet conditions. Additionally, shade can prevent wind damage to plants that otherwise would make them less resistant to the disease.

Shade also affects non-weather factors. Shade suppresses CLR by decreasing stomatal density (Avelino et al., 2004), which creates optimal conditions for another fungus, Lecanicillium lacanii, a natural parasite of the CLR fungus (Soto-Pinto et al., 2002; Staver et al., 2001; Shiomi et al., 2006; Jackson et al., 2012), and by reducing coffee crop yield (Avelino et al., 2006; Lopez-Bravo et al., 2012). Higher yield, or “fruit load,” is associated with higher incidence of CLR, and because fruit loads tend to be lower under shade, shade can reduce the incidence of CLR (Avelino et al., 2006; Lopez-Bravo et al., 2012).When berries are removed before they ripen, the severity of the infection decreases, possibly because the plants can contribute more toward resistance instead of fruiting (Kushalappa and Eskes, 1989). Leaves in full sun are more susceptible to CLR than leaves in the shade (Eskes, 1982). Conversely, shade can increase the incidence and/or severity of CLR by reducing solar radiation reaching the coffee plants and increasing leaf size, which increases the surface area onto which CLR spores can land (Avelino et al., 2004).

Farms with high coffee plant density tend to experience more frequent and severe disease outbreaks (Kushalappa and Eskes, 1989), possibly because the rust spores are easily transmitted from one plant to another, making control difficult; scientists have hypothesized that this phenomenon is due to the increased wetness associated with higher plant density (Paiva et al., 2011). Farms with greater biodiversity, however, may experience lower incidence of CLR because other plants can act as physical barriers to spore dispersal, help decrease wind speed and rain splash, and create an environment that is healthier and less prone to diseases and pests (Soto-Pinto et al., 2002; Avelino et al., 2012).

Although wind and rain splash are important dispersal mechanisms of CLR spores, humans have also played an important role in spore dispersal over both short and long distances. When infected leaves are touched, spores may be inadvertently transferred to other coffee plants. Movement of farmers and laborers can spread the disease throughout a single farm or to other farms that may be far away (Kushalappa and Eskes, 1989). There is some indication that CLR incidence is greater close to paths and residences than in less traveled areas, and new outbreaks may increase during and after harvests when people tend to come into contact with coffee plants more frequently (Waller, 1979). The spread of CLR across continents and oceans is primarily attributed to the transport of contaminated coffee seeds and plant materials, and to the movement of workers throughout a region (Kushalappa and Eskes, 1989). Scientists have hypothesized that wind transport of CLR may also have played a role in long-distance transport (Bowden et al., 1971), but there is no clear evidence of this to date.

Environmental stressors: Presence of spores, soil quality, and disease

The incidence and severity of CLR in one year may also play a significant role in outbreak intensity the following year, however there are conflicting findings in this regard. Some studies find that when incidence is high one year, more rust spores are available to spread to other leaves and plants the following year, thereby causing more outbreaks (Nutman and Roberts, 1970; Kushalappa and Eskes, 1989). The abundance of rust spores also affects the severity of the disease; more rust spores on any given leaf or plant leads to more severe damage (Kushalappa and Chaves, 1980 cited in Zambolim et al., 2016). More recently, however, it has been suggested that a low incidence is expected the year after a severe epidemic for two reasons: coffee yield has a biennial rhythm—when yield is high one year it tends to be lower on a given plant the next year—and severe epidemics cause intense defoliation, which reduces the amount of inoculum (Avelino et al., 2015).

Acidic soil can interfere with the uptake of nutrients, such as calcium, magnesium, and copper, making plants more vulnerable to CLR damage (Avelino et al. 2006). Other diseases that affect the coffee plant can weaken the plants and make them more vulnerable to CLR.

Other diseases that affect coffee can weaken the plants and make them more vulnerable to CLR.

Changes in Seasonal and Longer-Term Climate

Changing climate will have a number of potential negative impacts on agriculture worldwide, such as reduced crop yield due to heat stress, drought, extreme precipitation, and loss of cultivatable land (Solomon et al., 2007). Of greatest concern to CLR management efforts are the impacts of climate change on temperature and precipitation that will likely increase the incidence of CLR in the future (Avelino et al., 2015).

Warmer temperatures due to climate changes, particularly higher minimum temperatures, may create more favorable conditions for CLR in many coffee-growing regions and may also expand CLR's range into higher elevations (Avelino, 2013). Also, some coffee species grow best at temperatures below the optimum for CLR. For example, optimum temperatures for Arabica coffee—the most widely cultivated coffee species worldwide—are 18 to 21 degrees C. Higher temperatures can cause flowers to drop prematurely or fruit to ripen too quickly, diminishing the quality of the coffee (DaMatta and Ramalho, 2006). Therefore, increased average temperatures could create a double threat to coffee production.

Changes in the onset of rainy seasons may also affect CLR and plant health, where early onset of rains may extend the growing season for CLR and late onset may stress plants, making them more vulnerable to diseases (Georgiou et al., 2014). CLR outbreaks in Latin America in recent years have been associated with an earlier onset of the rainy season and also may have allowed CLR to proliferate more than in previous years (Georgiou et al., 2014). Changes in the total amount of precipitation also may affect CLR. However, the potential impacts of more or less precipitation on the disease and coffee plant vulnerability are not yet well understood.

Because climate change also affects seasonal climate variability, it is also possible that the range of temperatures and frequency and amount of precipitation can be affected in unexpected ways. For example, CLR outbreaks in Colombia in 2012–2013 have been attributed in part to above-normal minimum temperatures and below-normal maximum temperatures (Cristancho et al., 2012). This period was associated with La Niña conditions; for Colombia, other parts of northern South America, Central America, and the Caribbean, that meant increased cloud cover and precipitation and thus decreased solar radiation and a narrower range between daily maximum and minimum temperatures (Cristancho et al., 2012). These conditions led to more days with optimal conditions for CLR proliferation and potentially to shorter periods between plant infection and the development of new spores that could infect plants (Georgiou et al., 2014). It is unclear how climate change will affect the frequency and magnitude of El Niño and La Niña events, which exert a principal control on seasonal variability in many coffee-producing regions.

Less understood are the impacts of other new environmental conditions associated with climate change. Higher concentrations of carbon dioxide have been found to decrease the time between infection and production of new spores in laboratory conditions (Mendes, 2009; Ghini et al., 2011). If this occurs in natural conditions as well, it may speed up the disease cycle and lead to more severe outbreaks in the future.

Conclusions

The ability of farmers to manage CLR requires identifying early signs of the disease and being able to respond accordingly. Understanding the climate and weather connections to CLR outbreaks may allow farmers to prepare for and manage the disease more effectively, and ultimately reduce crop losses. Understanding the climate-CLR connection is especially important given that global climate change is likely to affect the incidence and severity of the disease in the near future.

SUGGESTED READING AND RESOURCES

Avelino, J., Willocquet, L., & Savary, S. (2004). Effects of crop management patterns on coffee rust epidemics. *Plant pathology*, 53(5), 541-547

Avelino, J., Zelaya, H., Merlo, A., Pineda, A., Ordoñez, M., & Savary, S. (2006). The intensity of a coffee rust epidemic is dependent on production situations. *Ecological modelling*, 197(3), 431-447

Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H. F., & Declerck, F. A. (2012). Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. *Ecological Applications*, 22(2), 584-596.

Capucho, A. S., Zambolim, L., Cabral, P. G. C., Maciel-Zambolim, E., & Caixeta, E. T. (2013). Climate favourability to leaf rust in Conilon coffee. *Australasian Plant Pathology*, 42(5), 511-514

Ghini, R., Bettiol, W., & Hamada, E. (2011). Diseases in tropical and plantation crops as affected by climate changes: current knowledge and perspectives. *Plant Pathology*, 60(1), 122-132.

McCook, S. (2006). Global rust belt: Hemileia vastatrix and the ecological integration of world coffee production since 1850. *Journal of Global History*, 1(02), 177-195

Soto-Pinto, L., Perfecto, I., & Caballero-Nieto, J. (2002). Shade over coffee: its effects on berry borer, leaf rust and spontaneous herbs in Chiapas, Mexico. *Agroforestry Systems,* 55(1), 37-45.

Staples, R. C. (2000). Research on the rust fungi during the twentieth century. *Annual Review Of Phytopathology*, 38(1), 49-69.

SOURCES CITED

Alves, M. D. C., de Carvalho, L. G., Pozza, E. A., Sanches, L., & Maia, J. D. S. (2011). Ecological zoning of soybean rust, coffee rust and banana black sigatoka based on Brazilian climate changes. *Procedia Environmental Sciences*, 6, 35-49.

Arneson, P.A. (2000). Coffee rust. The Plant Health Instructor. DOI: 10.1094/PHII2000071802. Updated 2011.

Avelino, J., Willocquet, L., & Savary, S. (2004). Effects of crop management patterns on coffee rust epidemics. *Plant Pathology*, 53(5), 541-547.

Avelino, J., Zelaya, H., Merlo, A., Pineda, A., Ordoñez, M., & Savary, S. (2006). The intensity of a coffee rust epidemic is dependent on production situations. *Ecological Modelling*, 197(3), 431-447.

Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H. F., & Declerck, F. A. (2012). Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. *Ecological Applications*, 22(2), 584-596.

Avelino, J. (2013). "The coffee rust (Hemileia vastatrix): Some biological and epidemiological aspects." Presentation to CIRAD, IICA-PROMCAFE, CATIE.

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., ... & Morales, C. (2015). The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. Food Security, 7(2), 303-321.

Avelino, J. (2016). "Effects of shade on coffee rust." Presentation at the Cumbre de Roya (Coffee Rust Summit) in Guatemala, 2016.

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., ... & Morales, C. (2015). The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. *Food Security*, 7(2), 303-321.

Becker, S. (1977). Diurnal periodicity in spore dispersal of hemileia vastatrix in relation to weather factors [coffee, kenya]. Zeitschrift fuer Pflanzenkrankheiten und Pflanzenschutz (Germany, FR).

Bock, K. R. (1962). Seasonal periodicity of coffee leaf rust and factors affecting the severity of outbreaks in Kenya Colony. *Transactions of the British Mycological Society*, 45(3), 289-300.

Boudrot, A., Pico, J., Merle, I., Granados, E., Vílchez, S., Tixier, P., ... & Rice, R. A. (2016). Shade Effects on the Dispersal of

Airborne Hemileia vastatrix Uredospores. Phytopathology, PHYTO-02.

Bowden, J., Gregory, P. H., & Johnson, C. G. (1971). Possible wind transport of coffee leaf rust across the Atlantic Ocean.

Brown, J. S., Kenny, M. K., Whan, J. H., & Merriman, P. R. (1995). The effect of temperature on the development of epidemics of coffee leaf rust in Papua New Guinea. *Crop Protection*, 14(8), 671-676.

Burdekin, D. A. (1960). Wind and water dispersal of Coffee leaf rust in Tanganyika. Kenya Coffee, 25(294), 212-213.

Capucho, A. S., Zambolim, L., Cabral, P. G. C., Maciel-Zambolim, E., & Caixeta, E. T. (2013). Climate favourability to leaf rust in Conilon coffee. *Australasian Plant Pathology*, 42(5), 511-514.

Cintra, M. E., Meira, C. A., Monard, M. C., Camargo, H. A., & Rodrigues, L. H. (2011). The use of fuzzy decision trees for coffee rust warning in Brazilian crops. In Intelligent Systems Design and Applications (ISDA), 2011 11th International Conference on (pp. 1347-1352). IEEE.

Corrales, D. C., Ledezma, A., Hoyos, J., Figueroa, A., & Corrales, J. C. (2014). A new dataset for coffee rust detection in Colombian crops base on classifiers. Sistemas y Telemática, 12(29), 9-23.

Cristancho, M. A., Rozo, Y., Escobar, C., Rivillas, C. A., & Gaitán, A. L. (2012). Outbreak of coffee leaf rust (Hemileia vastatrix) in Colombia. New Disease Reports, 25(19), 2044-0588.

DaMatta, F. M., & Ramalho, J. D. C. (2006). Impacts of drought and temperature stress on coffee physiology and production: a review. *Brazilian Journal of Plant Physiology*, 18(1), 55-81.

De Jong, E. J., Eskes, A. B., Hoogstraten, J. G. J., & Zadoks, J. C. (1987). Temperature requirements for germination, germ tube growth and appressorium formation of urediospores of Hemileia vastatrix. *Netherlands Journal of Plant Pathology*, 93(2), 61-71.

De Silva, N. T. M. H., & Tisdell, C. A. (1988). Strategies and administrative reforms to meet a biological threat to Papua New Guinea’s coffee industry. Agricultural Administration and Extension, 30(4), 309-323.

Eakin, H., Benessaiah, K., Barrera, J.F., Cruz-Bello, G.M., Morales, H. (2011). Livelihoods and landscapes at the threshold of change: disaster and resilience in a Chiapas coffee community. *Regional Environmental Change*, 12, 475-488.

Eskes, A. B. (1982). The effect of light intensity on incomplete resistance of coffee to Hemileia vastatrix. Netherlands Journal of Plant Pathology, 88(5), 191-202.

Ghini, R., Bettiol, W., & Hamada, E. (2011). Diseases in tropical and plantation crops as affected by climate changes: current knowledge and perspectives. *Plant Pathology*, 60(1), 122-132.

Georgiou, S., Imbach, P., Anzueto, F., Calderon, G., Avelino, J. (2014). “Weather and climate indicators for coffee rust disease.” Poster presentation at the 2014 American Geophysical Union conference.

Hoogstraten, J. G. J., & M Eskes, A. B. (1983). Influencia da umidade de solo e umidade relativa do ar sobre a resistencia do cafeeiro a Hemileia vastatrix. In 10. Congresso Brasileiro de Pesquisas Cafeeiras29 Ago-1 Set 1983Poços de Caldas, MG (Brasil) (No. 633.73063 C749 1983). Instituto Brasileiro do Café, Río de Janeiro (Brasil).

International Coffee Organization (ICO). (2013). “Report on the outbreak of coffee leaf rust in Central America and action plan to combat the pest.”

Jackson, D., Skillman, J., & Vandermeer, J. (2012). Indirect biological control of the coffee leaf rust, Hemileia vastatrix, by the entomogenous fungus Lecanicillium lecanii in a complex coffee agroecosystem. Biological Control, 61(1), 89-97

Kolmer, J. A., Ordonez, M. E., & Groth, J. V. (2009). The rust fungi. eLS.

Kushalappa, A. C., Akutsu, M., & Ludwig, A. (1983). Application of survival ratio for monocyclic process of Hemileia vastatrix in predicting coffee rust infection rates. *Phytopathology*, 73(1), 96-103.

Kushalappa, A.C., Chaves, G.M. (1980). An analysis of the development of coffee rust in the field. Fitopatol Bras 5:95–183.

Kushalappa, A. C., & Eskes, A. B. (1989). Advances in coffee rust research. *Annual Review of Phytopathology*, 27(1), 503-531.

Kushalappa, A.C., Hernández, T.A., Lemos, H.G. (1986). Evaluation of simple and complex coffee rust forecasts to time fungicide application. Fitopatol Bras 11:515–526.

Laderach, P., Lundy, M., Jarvis, A., Ramirez, J., Portilla, E. P., Schepp, K., & Eitzinger, A. (2011). Predicted impact of climate change on coffee supply chains (pp. 703-723). Springer Berlin Heidelberg.

López-Bravo, D. F., Virginio-Filho, E. D. M., & Avelino, J. (2012). Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. *Crop Protection*, 38, 21-29.

Luaces, O., Rodrigues, L. H. A., Meira, C. A. A., Quevedo, J. R., & Bahamonde, A. (2010). Viability of an alarm predictor for coffee rust disease using interval regression. In Trends in Applied Intelligent Systems (pp. 337-346). Springer Berlin Heidelberg.

Martínez, J. A., Palazzo, D. A., Karazawa, M., Monteiro, M. V. M., & Reu, N. R. N. (1975). Airborne spores of coffee rust Hemileia vastatrix Berk & Br. at differents altitudes, in the main coffee plantation areas of the states of Sao Paulo and Paraná (Brazil). Presença de esporos de Hemileia vastatrix Berk et Br. agente causal de ferrugem do cafeeiro, em diferentes altitudes nas principais areas cafeeiras dos estados de Sao Paulo e Parana, Brasil. Biologico (Brasil).

Martinez, J. A., Palazzo, D. A., & Karazawa, M. (1977). Importance of the wind in the release and dissemination of spores of Hemileia vastatrix Berk & Br. Fitopatologia Brasileira, 2(1), 35-42.

McCook, S. (2006). Global rust belt: Hemileia vastatrix and the ecological integration of world coffee production since 1850. *Journal of Global History*, 1(02), 177-195.

Meira, C. A. A., Rodrigues, L. H. A., & Moraes, S. A. D. (2009). Warning models for coffee rust control in growing areas with large fruit load. Pesquisa Agropecuária Brasileira, 44(3), 233-242.

Mendes L, (2009). Impacto do Aumento da Concentrac¸a˜o de CO2 Atmosfe´rico sobre o Perı´odo Latente e o Controle Biolo´ gico da Ferrugem do Cafeeiro. Botucatu, Brazil: UNESP, MSc dissertation. Cited in Ghini et al., 2011.

Nutman, F. J., Roberts, F. M., & Bock, K. R. (1960). Method of uredospore dispersal of the coffee leaf-rust fungus, Hemileia vastatrix. *Transactions of the British Mycological Society*, 43(3), 509IN5-515IN6.

Nutman, F. J., Roberts, F. M., & Clarke, R. T. (1963). Studies on the biology of Hemileia vastatrix Berk. & Br. *Transactions of the British Mycological Society*, 46(1), 27-44.

Nutman, F. J., & Roberts, F. M. (1970). Coffee leaf rust. PANS Pest Articles & News Summaries, 16(4), 606-624.

Paiva, B. R. T. L., Souza, P. E. D., Scalco, M. S., & Santos, L. A. (2011). Progress of rust in coffee plants in various densities of cultivation in irrigated planting after pruning. Ciência e Agrotecnologia, 35(1), 137-143.

Perez-Ariza, C. B., Nicholson, A. E., & Flores, M. J. (2012). Prediction of coffee rust disease using bayesian networks. In Proceedings of the Sixth European Workshop on Probabilistic Graphical Models (pp. 259-266).

Rayner, R. W. (1961). Germination and penetration studies on coffee rust (Hemileia vastatrix B. & Br.). *Annals of Applied Biology*, 49(3), 497-505.

Santamaría, J., & Bayman, P. (2005). Fungal epiphytes and endophytes of coffee leaves (Coffea arabica). Microbial Ecology, 50(1), 1-8.

Shiomi, H. F., Silva, H. S. A., Melo, I. S. D., Nunes, F. V., & Bettiol, W. (2006). Bioprospecting endophytic bacteria for biological control of coffee leaf rust. Scientia Agricola, 63(1), 32-39.

Silva Acuña, R., Silva Acuña, A. & Zambolim, L. (1998) Indice estomático en materiales genéticos de café resistentes o susceptibles a la roya. Bioagro, 10, 57-61.

Soto-Pinto, L., Perfecto, I., & Caballero-Nieto, J. (2002). Shade over coffee: its effects on berry borer, leaf rust and spontaneous herbs in Chiapas, Mexico. *Agroforestry Systems*, 55(1), 37-45.

Staver, C., Guharay, F., Monterroso, D., & Muschler, R. G. (2001). Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agroforestry Systems*, 53(2), 151-170.

Sutton, J. C., Gillespie, T. J., & Hildebrand, P. D. (1984). Monitoring weather factors in relation to plant disease. *Plant Disease*, 68(1), 78-84.

Waller, J. M. (1979). The recent spread of coffee rust (Hemileia vastatrix Berk. & Br.) and attempts to control it. *Plant Health*, 275(283), 1980.

Waller, J. M. (1982). Coffee rust—epidemiology and control. *Crop Protection*, 1(4), 385-404

World Coffee Research (WCR). (2014). “Revitalizing the Central American Coffee Sectors after the Rust Crisis of 2012. Brief update and industry response through research and development.”

Zambolim, L. (2016). Current status and management of coffee leaf rust in Brazil. Tropical Plant Pathology, 41(1), 1-8.

OTHER PEER-REVIEWED ON CLR PAPERS NOT REFERENCED:

Bowden, J., Gregory, P. H., & Johnson, C. G. (1971). Possible wind transport of coffee leaf rust across the Atlantic Ocean.

reviewed by:
Jacques Avelino, CIRAD-CATIE-IICA/PROMECAFE (May, 2016)

suggested citation:
Rountree, V. and Guido, Z. (2016). Links Between Coffee Leaf Rust, Weather, and Climate: A Literature Review. International Research and Applications Project, Univeristy of Arizona and Columbia University.

photo credits:
Zack Guido

SUPPORTED BY